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The geomorphology and surface processes of the Australind-Leschenault Inlet coastal area

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Abstract

The Australind-Leschenault Inlet area, near Bunbury Western Australia, is in the southern part of the Swan Coastal Plain. The development of the geomorphology is related to the physical features of climate (rainfall, the evapo-transpiration regime and wind) and oceanography. Wind is an important element in that it mobilises sand and also generates local waves. Tidal influence is minimal and the main oceanographic features include a wave-dominated coast subject to swell and wind waves, and a protected lagoon subject to locally generated wind waves.

Four major geomorphic units are recognised: (1) a hinterland, composed of Bassendean, Spearwood and Blythewood units; (2) Leschenault Inlet, a narrow lagoon; (3) Leschenault Peninsula, which is a narrow barrier of dunes referable to the Quindalup system and (4) a nearshore submarine shelf. Three of these units are further divided into geomorphic sub-units. The Leschenault Inlet system contains samphire and sedge (tidal) flats, sand shoals and platforms and an interior basin. The Leschenault Peninsula contains a beach/beach ridge system on the western side, mobile and fixed dunes over most of its surface and predominantly vegetated dunes and woodland plains on its eastern side. On the peninsula there is contemporary development of soils and subsurface cementation. The submarine shelf is underlain mainly by Tamala Limestone and ridges of beachrock; locally there are outcrops of basalt and relic muddy estuarine deposits. Beachrock is forming in the subsurface along the shoreface of the peninsula and is exposed by periodic coastal retreat.

Major processes important to the development of Holocene geomorphology are sedimentation and erosion. Sedimentation sites include (1) Leschenault Inlet, (2) the zone of dune encroachment along the eastern side of the peninsula and (3) local pockets of beach-ridges. Mobile dunes ultimately spill into the inlet and thus there is a progressive migration of the barrier across the inlet. Wind and wave erosion however are prevalent and dominant processes in developing the coastal morphology (steep cliffed dune line, eroding hollows) and the submarine shelf morphology. Removal of sediment in the shore zone results in a nearshore beachrock ridge system left in the wake of coastal retreat and an offshore pavement of Tamala Limestone. The bulk of the coastal sediment is moving in a net northerly direction out of the study area.

Introduction

The region of Australind-Waterloo Head-Leschenault Inlet-Koombana Bay (near Bunbury) on the southern portion of the Swan Coastal Plain (Fig. 1) contains a number of landform units, Pleistocene to Holocene in age (McArthur and Bettenay 1960). As a result of research in this area new information was obtained that adds to the detail on the geomorphic evolution of the coastline. The data also gives insight into some processes of coastal development on the broader context of the Swan Coastal Plain.

The data and interpretations will be presented in a series of papers on various inter-related aspects of natural history of the area. This paper presents the geomorphic framework essential to the appreciation of other papers on stratigraphy and geologic history (Semeniuk in prep.) and habitats and biology (Semeniuk and Blackwell in prep.). As such this paper describes the main geomorphic units and the key processes important to the development of the area.

Methods

A broad range of techniques was used to assemble the data presented here. These included:

1. A review of the aerial photographic record taken over the area in 1940, 1966, 1971, 1974 and 1978. The photographs are available from the Western Australian Department of Lands and Surveys.
2. The identification and surface mapping of the major geomorphic and stratigraphic units.
3. An examination of the near-surface stratigraphy in 55 small backhoe excavations, in 8 large costeans made by bulldozer and drag line, and along wind and wave-eroded cliff faces particularly after some severe storms.
4. An examination of the seafloor topography and stratigraphy by diving. Samples of the seafloor bedrock were collected by blasting.

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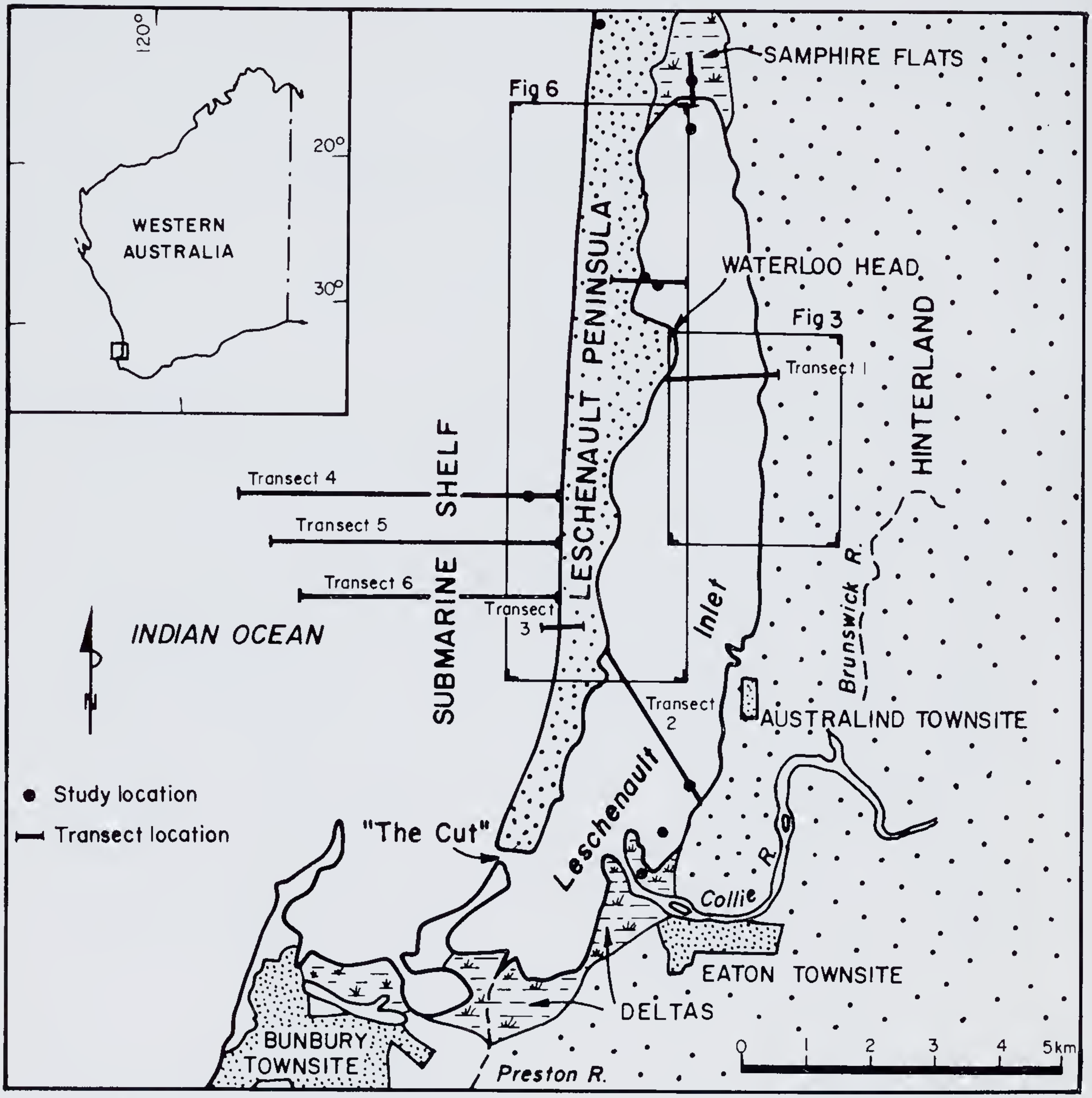

Figure 1.—Map of study area showing main geomorphic units and geographic features mentioned in text. Locations of more detailed maps, transects and study sites also are shown.

5. Coring to depths of 8-30 m with both diamond drill and percussion-coring devices to obtain some 70 cores; core data are presented in Semeniuk (in prep.).

6. Documentation by observation and photography of the modern surface and near-surface processes; this has elucidated the mechanisms by which the stratigraphy, hydrology, geochemistry and biology have developed. Some of these data provide analogues of material found in core.

From these sample sites, some 2 000 sediment samples were collected and examined under binocular microscope for structure, fabric, texture and gross (mineral) composition. Selected samples were disaggregated under the microscope and tested for carbonate with hydrochloric acid. Standard laboratory analyses were made on some samples; these included: grain-size analysis by seiving and thin section (48 samples), X-ray diffractometry (16 samples), chemical analyses for calcium carbonate and ferrous iron content (62 samples). An additional 200 sediment samples from selected intervals at depth have been analysed for a range of constituents by the Government Chemical Laboratories. These results were incorporated in our study of sedimentary profiles.

Regional setting

The processes influencing the formation of landforms today are related to the physical phenomena of climate (rainfall, evaporation and wind) and oceanography. These also influence the distribution of sediment types and the formation of stratigraphic units. The physical characteristics of the environment essential to the geomorphic processes are outlined below.

Climate

The climate of the area is typically Mediterranean with hot dry summers and mild wet winters. Annual precipitation is 881 mm (average) falling mainly in April to November. Temperatures reach a mean maximum of 27.9°C in January. The corresponding mean maximum for winter occurs in August at 16.5°C. The mean minimum temperature in winter is 8.3°C. Climatic data are presented in Table 1 (Bureau of Meteorology 1975).

Wind is important in this area for its role in movement of sand and in the generation of waves along beach faces. Measurements of wind collected at Bunbury (Steedman pers. comm. 1979) summarise the wind regime for the study area (Table 2 and Figure 2B). Analysis shows clearly the division between the summer and winter wind patterns prevailing over the region. Normal wind patterns are related to the position of the eastward-travelling high and low pressure systems which control the weather (Gentilli 1972).

The winter period is characterised by storms with intervening relatively calm weather. The storms typically have mean wind speeds up to 20 m/s for 6-24 hour durations, and mainly prevail from the north-west, west and south-west sectors. Two to four of these storms may be expected each winter, with minor storms occurring approximately every 2 weeks.

As summer approaches the high pressure systems move north and the regional wind conditions moderate. Sea breeze/land breeze systems then control the winds in the coastal area. This results as the differences between the land and sea temperatures dominate the winds, particularly in the summer afternoon periods when the sea breeze blows from the west to south-west with speeds up to 15 m/s.

During the summer there is the possibility of tropical cyclones travelling through the area. Although they are weakening, these storms are still capable of producing extreme wind and waves. Late summer to autumn is the calmest period of the year with light winds.

The important elements of the wind pattern in moving sand are that in summer wind blows onshore during the afternoon with far more strength and duration than does the opposing wind from the land. Figure 2 shows that sand-shifting speeds (i.e. > 4.5 m/s) near ground level occur predominantly from south-west to north-west quarters associated with sea

Table 1

Climatic data for Bunbury (from Bureau of Meteorology 1975)

Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean rainfall (mm)	10	12	23	46	129	186	174	126	81	55	25	14	881
Mean no. raindays	3	3	4	8	14	18	20	17	14	11	6	4	122
Daily mean maximum temperature (°C)	27·4	27·9	25·6	21·7	19·6	17·5	16·7	16·5	17·6	20·1	22·3	25·9	21·6
Daily mean minimum temperature (°C)	16·5	16·6	14·9	12·9	10·7	9·8	9·1	8·3	9·5	10·9	12·7	15·0	12·2
9 a.m. mean relative humidity (%)	63	62	67	77	75	81	78	76	73	67	65	63	71
3 p.m. mean relative humidity (%)	59	54	57	64	62	69	69	67	64	62	61	59	62

Table 2

Annual wind velocity data, Bunbury Power Station, January to December 1977. *The body of the table shows the relative frequency as a percentage.*

Direction(²)	Wind speed (m/s)(¹)								
	0–2	2–4	4–6	6–8	8–10	10–12	12–14	>14	Totals
North	0·6	0·9	2·2	1·1	0·4	0·3	0·2	0·3	5·8
North-east	0·9	1·3	1·6	0·3	0·1	*	*	*	4·4
East	3·0	2·7	3·4	0·6	0·1	*	*	*	9·9
South-east	5·4	4·5	6·9	2·0	0·3	0·1		*	19·2
South	6·1	5·4	7·4	1·9	0·4	0·1			21·3
South-west	2·5	2·5	4·2	1·1	0·3	0·1	*	*	10·7
West	0·9	1·3	6·8	3·7	1·6	1·0	0·4	0·3	16·0
North-west	0·6	1·1	3·5	2·3	1·5	0·9	0·5	0·4	10·8
Totals	20·0	19·8	36·0	13·0	4·7	2·6	1·1	1·0	

Percentage calm = 1·9 No. of readings = 8 752

Note:
* Denotes occurrence is <0·05%.
(¹) Speed,s, in e.g. group 2–4 implies 2·0 <s ≤4·0 etc.
(²) Direction groups 22·5 ° either side of specified direction.

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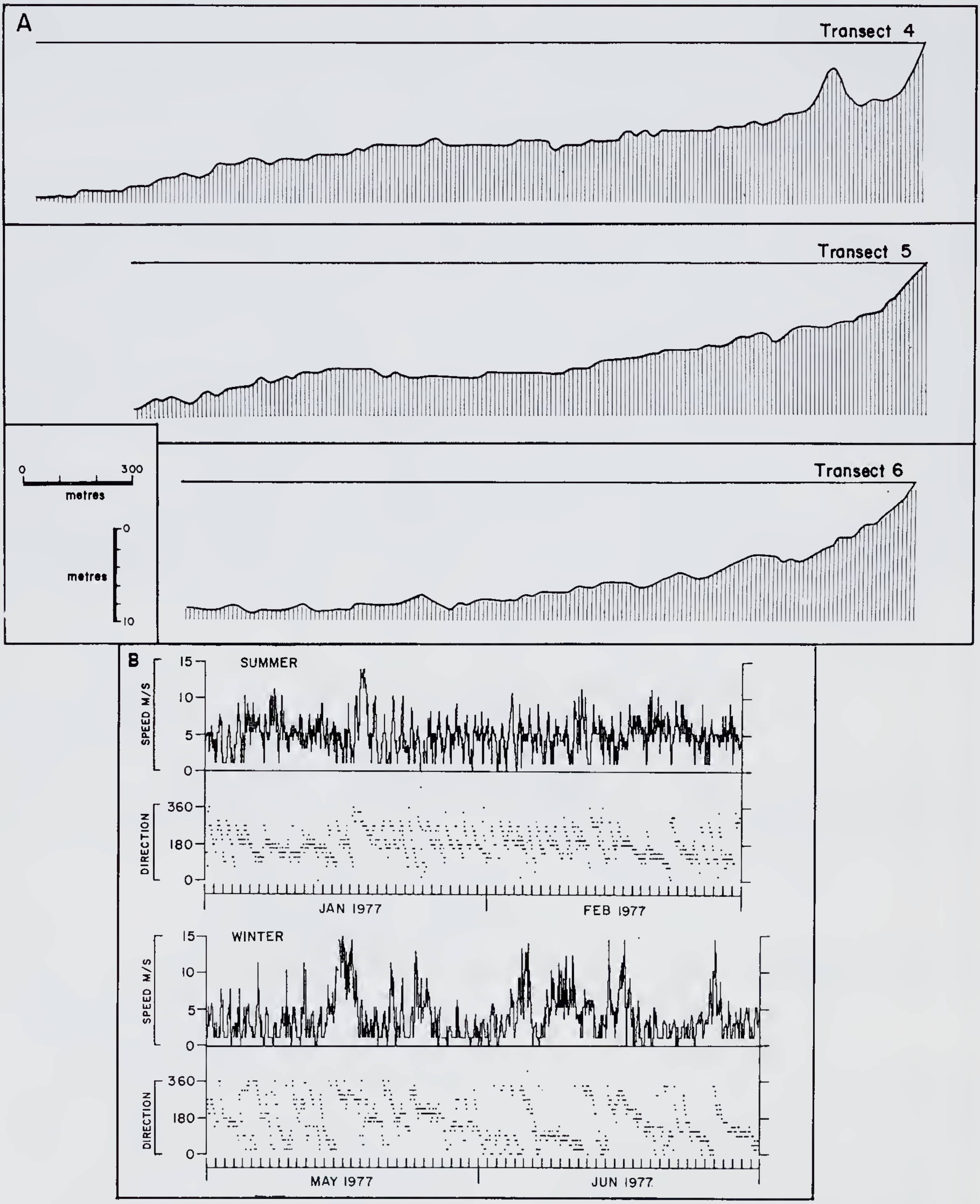


Figure 2.—A.—Bathymetric profiles of the submarine shelf along transects 4, 5 and 6 (see Fig. 1 for location). B.—Examples of the pattern of variation of wind speeds and direction (10 m above surface) during summer and winter, typical of the Bunbury area.

Figure 3.—A.—Map showing geomorphic elements of the hinterland and Leschenault Inlet. B.—Bathymetric profile across transect 1. C.—Summary of the range of soils and shallow stratigraphy representative of each of the geomorphic sub-units in map A.

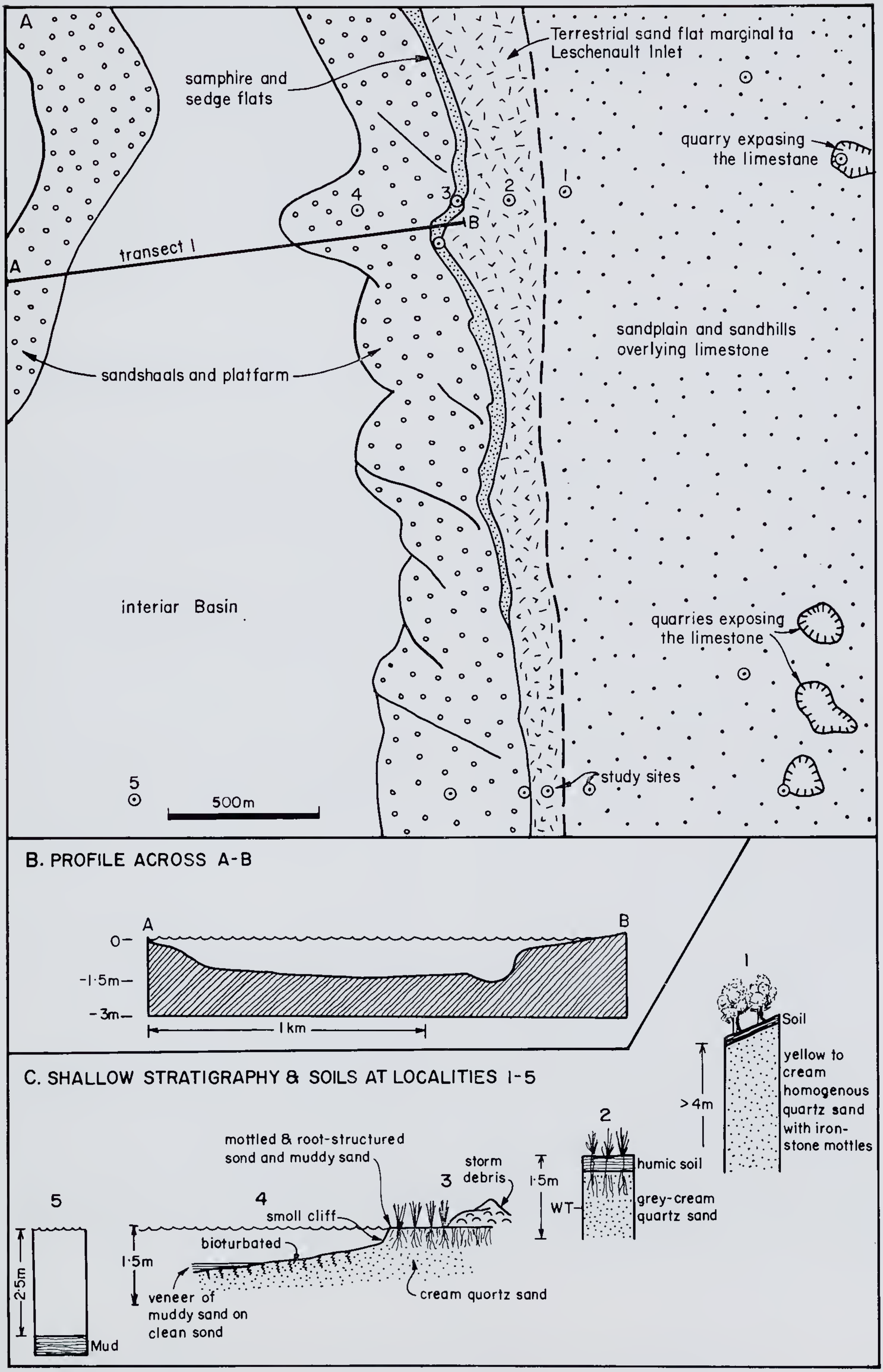

A
Terrestrial sand flat marginal to Leschenault Inlet
samphire and sedge flats
quarry expasing the limestone
4
3
2
1
B
transect I
A
sandplain and sandhills overlying limestone
sandshoals and platfarm
interiar Basin
quarries exposing the limestone
5
500m
study sites
B. PROFILE ACROSS A-B
A
B
0
-1·5m
-3m
1 km
C. SHALLOW STRATIGRAPHY & SOILS AT LOCALITIES 1-5
1
Soil
>4m
yellow to cream homogenous quartz sand with iron-stone mottles
2
humic soil
1·5m
WT
grey-cream quartz sand
mottled & root-structured sond and muddy sand
3
storm debris
5
4
smoll cliff
bioturbated
2·5m
1·5m
veneer of muddy sand on clean sond
cream quortz sand
Mud

Table 3

Predicted locally wind-generated wave heights by direction using the 1977 Bunbury Power Station wind records. The body of the table shows relative frequency as a percentage (rounded to nearest 0·1 %).

Direction (Deg.)	Significant wave height in metres †								
	0·0–0·2	0·2–0·4	0·4–0·6	0·6–0·8	0·8–1·0	1·0–1·2	1·2–1·4	1·4–1·6	1·6–1·8
338–22	0·3	0·7	0·1	0·1	*	....	....	....	....
23–67....	3·1	1·1	0·1	*	*	....	....	....	....
68–112	9·3	0·5	*	....	*	....	....	....	*
113–157	13·0	5·8	0·3	....	....	....	....	....	....
158–202	8·0	6·2	4·3	1·4	0·6	0·3	0·1	*	....
203–247	3·2	1·7	1·9	2·2	0·1	0·7	0·2	0·3	0·1
248–292	1·4	0·9	2·2	4·3	0·4	2·2	0·6	1·0	0·7
293–337	0·9	0·8	1·3	2·1	0·1	1·3	0·4	0·6	0·6

The matrix was computed by R. K. Steedman and Associates using the SMB Method. This is a procedure developed by Sverdrup and Munk (1947) and modified with additional empirical data by Bretschneider (1959). Wave data generated for a water depth of 10m. The matrix does not include the persistent westerly and south-westerly swell that arrives in the area from storms in the southern Indian Ocean.

* denotes occurrence is $<0 \cdot 05\%$.

† Wave height in group 0·2–0·4 implies $0 \cdot 2 < \text{wave height} \leqq 0 \cdot 4$, etc.

breezes. As a result there is a net mobilisation of the dry sand of the beach and dunes from the west to east across the peninsula. Figure 2B also shows a large proportion of sand-shifting wind occurs in summer. During winter there is a less frequent occurrence of sand-shifting wind, near ground level; those that do occur come from the south-west to north-west quarters; however the unconsolidated beach sands and mobile dunes of the peninsula tend to be damp and are therefore less prone to mobilisation by wind.

Oceanography

The Leschenault Peninsula is bounded by the Indian Ocean. However, the seafloor in this region is shallow for a substantial distance offshore (Figure 2A). As a result the wave and swell regime is markedly attenuated on reaching the beach; during storm conditions, the wave regime is further modified by a series of reefs lying close and parallel to the existing shoreline. The predominant forces of the wave regime along the coast are due to the combination of swell and wind/wave. The net transport of beach sediment is dependent largely upon the orientation of wave attack. Table 3 summarises data on significant wave height generated by wind. This shows the predominant wind waves that impinge on the coast are from the west and south-west sectors. When these are combined with the predominantly west and south-west swell there is a net northward movement of sediment in the shore zone.

An important element in the erosion of this beach is astronomical and storm tidal levels. The Bunbury region has a very small tidal amplitude (Hodgkin and Dilollo 1957). The tides are diurnal and have the following ranges (Australian National Tide Tables 1979):

Highest astronomical tide (HAT)	+ 1.3 m
Mean higher high water (MHHW)	+ 0.9 m
Mean sea level (MSL)	+ 0.6 m
Mean lower low water (MLLW)	+ 0.4 m
Lowest astronomical tide (LAT)	0.0 m

However mean sea level is influenced markedly by barometric pressure. During summer the area is dominated by high pressure systems which give way to low pressure systems during winter. As a result, there is a general shift in mean sea level of up to 0.5 m between winter and summer. During winter storms, the low pressure accompanying storms together with wind stress on the sea toward the coast combine to ensure that storm wave attack tends to be high up the beach. Net erosion, however, can have an irregular pattern from year to year. Consequently there are a number of seasons with only minor erosion and in occasional years, with intense erosion.

Leschenault Inlet is a shallow elongated lagoon with water depth less than 2 m. Wave energy within Leschenault Inlet is due entirely to local wind waves. During summer wind waves generated by the sea breeze are sufficient to suspend muds from the shallow floor of the inlet.

The hydrologic characteristics of the water within Leschenault Inlet have changed recently. Prior to 1951 the entrance of Leschenault Inlet to the sea was at the southern end of Koombana Bay. Both the Collie and the Preston Rivers entered Leschenault Inlet and, together with substantial drainage from the north, they exerted a fresh water influence at the end of winter. As a result, the general characteristic of Leschenault Inlet was brackish during winter and marine during summer (Rochford 1951, Meagher 1971). After making an artificial entrance (referred to locally as "The Cut", Fig. 1) to the lagoon adjacent to the two rivers, the hydrology changed virtually to that of a marine embayment. Brackish water influences now are much reduced and the inlet remains essentially marine in salinity throughout much of the year other than for the occasional outflow conditions from the Collie and Preston rivers. The outflow from the Collie River also has been substantially reduced as a result of the catchment upstream.

There was a far higher incidence of flooding over the surrounding land along the eastern foreshores of Leschenault Inlet prior to the development of the Bunbury region (with the consequent impounding of water from the Collie River and the artificial channel cut through the lagoon). Thus geomorphic influences have been substantially changed within the last 100 years. The higher incidence of flooding and the retention of water in low-lying areas further into summer, could be expected to influence not only the aquatic vegetation and fauna of Leschenault Inlet but also the strandline vegetation and sediments peripheral to the inlet.

1·8–2·0	2·0–2·2	2·2–2·4	2·4–2·6	2·6–2·8	2·8–3·0	3·0–3·2	3·2–3·4	3·4–3·6	3·6–3·8	3·8–4·0	4·0–+
....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....
*	0·2	0·1	....	*	....	....	*	....	....	....	....
0·1	0·8	0·8	0·1	0·2	*	0·1	0·2	0·1	0·1	0·1	0·2
0·1	0·8	0·5	*	0·3	*	0·1	0·2	0·1	*	0·1	0·2

No. of data points = 8 744
Mean wave height = 0·5
Maximum wave height = 5·4

Standard deviation = 0·7
Percentage calm = 2·8

Geomorphic units

The study area is located toward the southern end of the Swan Coastal belt (Jutson 1950, Gentilli and Fairbridge 1951). Most of the land surface of this area is composed of sediments of Pleistocene to Holocene age which have been deposited in a range of marine, fluviatile, lacustrine and aeolian environments (Seddon 1972).

In the immediate vicinity of Leschenault Inlet there are 4 major geomorphic units based on the criteria of physiography, sedimentary materials and biological habitat. From east to west these are (Fig. 1): (1) hinterland, (2) inlet, (3) peninsula and (4) submarine shelf.

Within the peninsula and inlet units, sedimentation is still continuing. As a result there are modern analogues of much of the material examined in excavation, cliffs and in cores. The ocean shore portions of the peninsula and the submarine shelf are in a predominantly erosional phase. Many geological features of the nearshore area are the result of a retreating coast and an exhumed old surface (unconformity).

Hinterland

Hinterland is a convenient term used here to describe the aggregate of land units (Spearwood, Bassendean, and Blythewood units; McArthur and Bettenay 1960) to the east of Leschenault Inlet. The land surface is undulating with average relief generally less than 20 m; some local areas have relief up to 30 m above sea level. The hinterland is covered by a variety of soils (McArthur and Bettenay 1960). Each of these has a recognisable vegetation assemblage (Seddon 1972). In broad terms, these vegetation assemblages range from *Eucalyptus* and *Banksia* forests and woodlands in the higher areas (where they have not been cleared for agriculture) and *Melaleuca* wetlands in the lower areas.

Figure 3 shows the distribution of sedimentary materials adjacent to the foreshore of Leschenault Inlet. The main sedimentary materials are: Tamala Limestone (Playford *et al* 1976)—Spearwood Dune System (McArthur and Bettenay 1960), (2) Quartz sands overlying the Spearwood Dune System and Bassendean Dune System (McArthur and Bettenay 1960) and (3) Fluviatile, lagoon and deltaic sediments—Vasse and Blythewood Systems (McArthur and Bettenay 1960).

Inlet

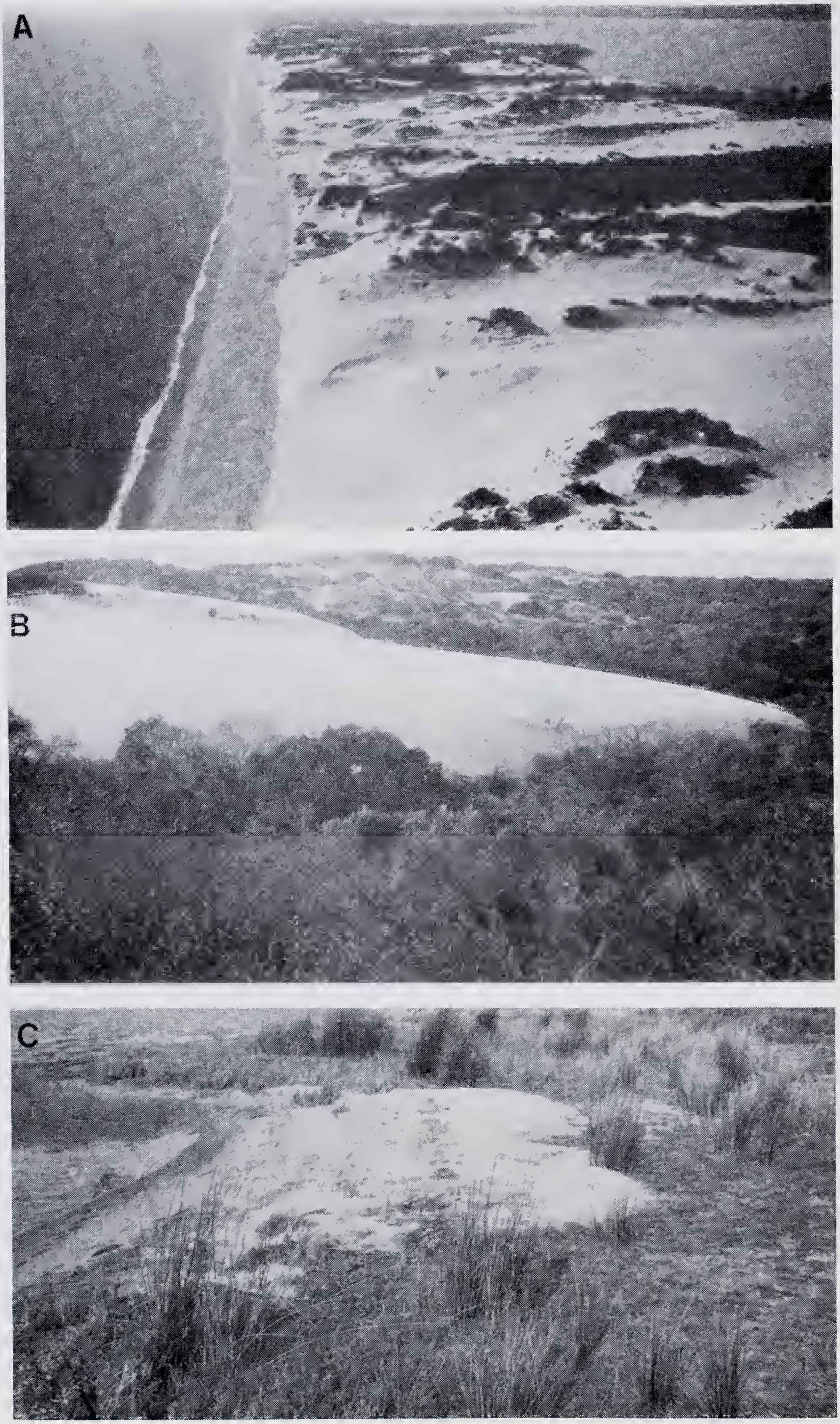
The Leschenault Inlet is a lagoon some 14 km long, between 1.5 km and 2.5 km in width and 0.3 m to 2 m in depth which lies parallel to the coast and is separated from the Indian Ocean by a narrow barrier. It can be subdivided into 3 geomorphic sub-units; these are sedimentologically and biologically distinct and can be related readily to depth of water. The sub-units are (Fig. 3): (1) samphire and sedge flats, (2) sand shoals and platforms and (3) interior basin.

Samphire and sedge flats. Strandline flats, inundated by high-tide and stormwater level, are covered by vegetation such as samphires *Arthrocnemum bidens* and *Suaeda australis* and the sedge *Juncus.* Shoreline trees such as *Melaleuca raphiophylla, M. cuticularis, Casuarina obesa,* and the mangrove *Avicennia marina* occur in scattered and individual copses.

Sediments underlying the surface of this zone are variable; mostly they are root-structured muds, or muds burrowed with sand/mud mixtures and organic detritus. Locally substrates are predominantly sand. Sediments are grey to black due to organic detritus and iron sulphide. Along the eastern shoreline there are local ribbon and shoe-string deposits (5-30 mm thick) of shelly gravel, coarse sand and organic detritus. They have formed by shoreward transport and accumulation of sedimentary materials during storms (Fig. 4C) which are accompanied by elevated water levels and strong wind waves.

Sand shoals and platforms. Shallow sand shoals and platforms occur along both sides of the inlet (Figs. 3, 5) between MHHW and 0.2 m below MLLW. They become (partially) exposed during a combination of low tide and high barometric pressure.

Shoals are the subaqueous terminal portions of sand dunes that extend into Leschenault Inlet. On the western side they are due to the progradation of the mobile dunes; on the eastern side they are due to the encroachment of the inlet on the old dunes of Pleistocene age. Reworking and mobilisation by currents and waves results in cusps and spits along the shoreline at the tip of shoals.


A
B
C

Platforms are narrow units that border the remaining coastline of the inlet; their margins are straight, gently curved or lobate. Platforms originate as wave-built and current-modified features formed from sediment eroded off dunes and sandhills adjoining the inlet. Sediments of shoals and platforms are derived from quartz calcareous sands on the west margin, and from siliceous sands on the east margin of the inlet.

Vegetation on sand shoals and platforms consists of a number of unattached and semi-attached algae together with the seagrasses *Zostera* and *Halophila*. The top layers of sediment are well bioturbated by a range of crustaceans, worms and fish. Mollusc fauna of the platforms contribute shells to the sands. Mud layers that accumulate on the surface during quiescent periods are mixed into the sediment by

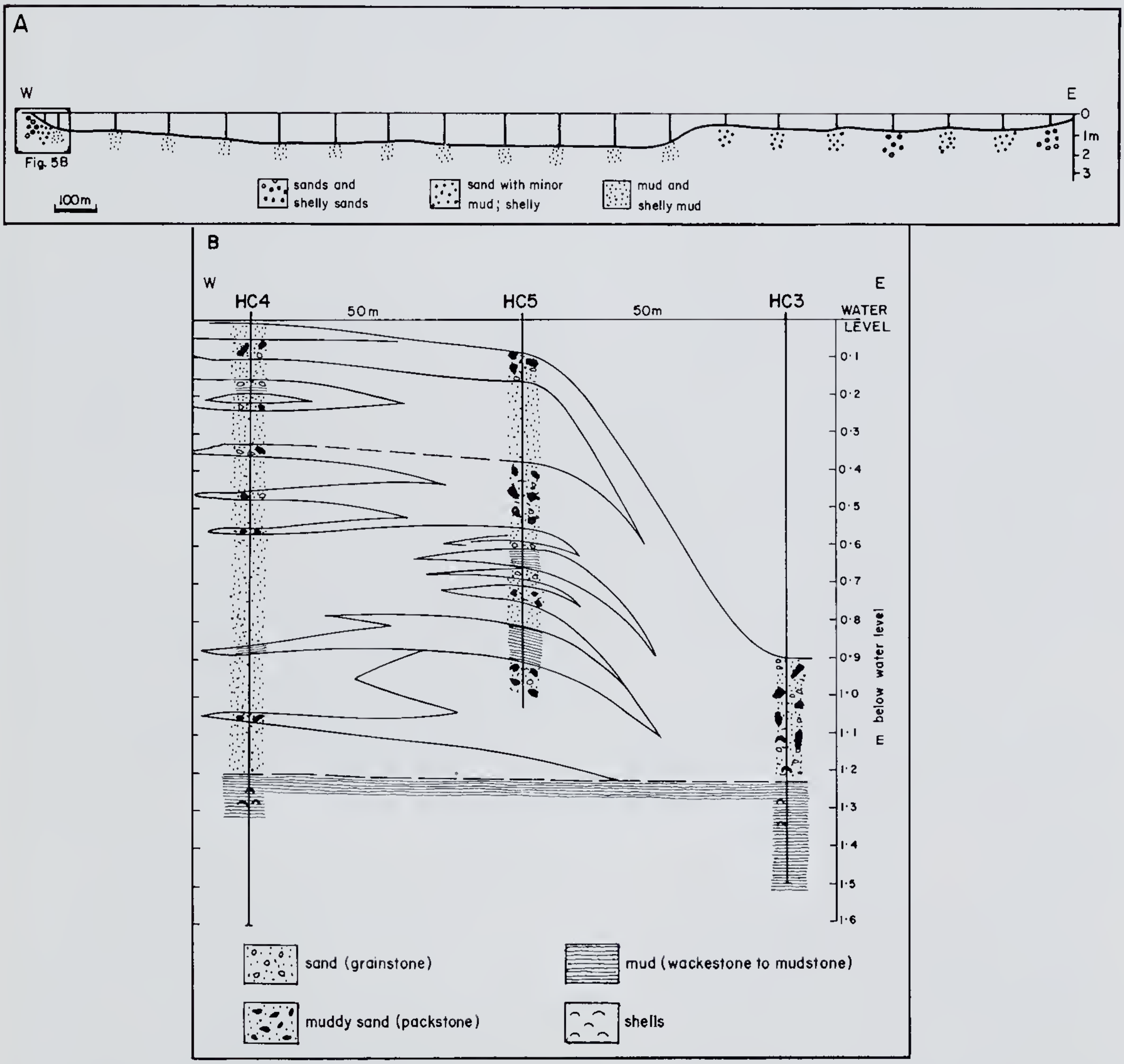


Figure 5.—A.—Bathymetric profile and surface sediment types along transect 2 (see Fig. 1) across Leschenault Inlet. Shoals and platforms on the shallow margins are composed of sand and muddy sand; the deeper interior basin is floored by mud. B.—Detail of inset. The profile illustrates the variability of shallow stratigraphy within a shoal. Water level is MSL.

Figure 4.—A.—Aerial view of Leschenault Peninsula. Its seaward edge is clearly marked by the narrow ribbon of orange-stained beach and beach ridge sands (light grey on photograph); these abruptly adjoin the white sands of the eroding dune line. The bulk of the Peninsula is composed of bare and mobile dunes interspersed with vegetated dunes. B.—Advancing front of a mobile dune, here encroaching upon a heath-covered dune. The mobile dune is an attenuated parabolic form which appears as an east-west elongated finger of sand. The location of this dune is shown arrowed on Figure 6. C.—Strandline storm deposits of sand, shell and vegetation debris tossed up onto the sedge and samphire flat along the margin of Leschenault Inlet.

burrowing organisms. Thus, depending on intensity of biological activity and rate of mud influx, the sand shoal and platform areas have varying proportions of shelly sand, muddy sand and burrowed clean sand.

Interior basin. At the edge of a shoal or a platform there is often a marked slope (Figs. 3, 5) which falls from 0.2 m to 1.0 m below MLLW into the interior basin (maximum 3 m deep). The basin floor is dark grey to brown mud and some muddy sand. Resident animals contribute shells and burrow the sediment so that bioturbated, shelly muds are developed locally.

Relationships. Leschenault Inlet is quite obviously filling with sediment. Sand derived from margins extends into the inlet interfingering with, and prograding over, muddy sediments. The continuing *in situ* yield of seagrass and algae contributes humic material. The associated mollusc fauna contributes calcium carbonate debris.

Wave action and littoral drift along the inlet result in accumulation of muds on the shallow flats. Mud is commonly deposited on the western shore as a veener on sand. Mud is winnowed off the eastern sand platforms each day when the sea breeze generates small waves and induces long-shore drift. Some of this mud finds its way into the interior basin, but a significant amount of mud also is transported northwards and accumulates in a thick wedge along the northern inlet margin. There are 4 sources of mud: (1) rivers that drain into the embayment, (2) erosion of older, muddy estuarine deposits, (3) fine-grained organic detritus derived from breakdown of aquatic plants and (4) skeletal silt generated within Leschenault Inlet.

Typical transects across a shoal into the interior basin are illustrated in Figures 3 and 5. The shoals have prograded over mud floors which consistently occur at about 1.0-1.5 m below MLLW.

Peninsula

The peninsula separates the inlet from the sea and is an elongated barrier some 12 km long and between 0.8 km and 1.5 km in width (Fig. 4A). Its surface is undulating and consists of a series of vegetated and mobile sand dunes whose elevation ranges from near sea level to 40 m. These dunes have been assigned to the Quindalup system by McArthur and Bettenay (1960).

Beach sands occur along the western side of the peninsula and pass inland into bare exposed dunes. Vegetated dunes become more common toward the east. Along the eastern side of the peninsula, there is low-lying, flat land which has a cover of humic soil and coastal vegetation interspersed with vegetated dunes and mobile dunes. In some areas mobile dunes extend as tongues of sand into Leschenault Inlet.

Photographs taken during the 1940s, show that although some individual dunes have migrated significantly to the east, the distribution of dunes and vegetation along the peninsula is broadly the same as today. The photographs also indicate that this landform has been a natural peninsula which extended down the western margin of the inlet to its narrow entrance to Koombana Bay.

The Leschenault Peninsula is readily separated into 4 geomorphic sub-units:—(1) beach and beach ridge, (2) mobile dunes, (3) vegetated dunes and (4) woodland plain.

Beach and beach ridge. This zone encompasses both the beach-face and the supra-tidal storm ridge accumulations (Figs. 4A, 6). Sand, lithoclast gravel and shells comprise the beach and beach ridge sediment (Fig. 7A). The source of the material is local (derived directly from eroding dunes), nearshore (rocks, shells and sand from adjoining reefs) and offshore (coarse sand, shells, mud clasts and rocks). Waves and long-shore currents dominate the physical environment. As a result, sediments are laminated and cross-laminated. The mobile, shore sands have been artificially stained orange by iron within the last decade by factory effluent from processing of titanium minerals. Consequently the abrupt contact of the youngest beach/beach ridge sediments with both older beach/beach ridge sediments and other units is well marked (Figures 4A and 7B).

Mobile dunes. Parabolic mobile dunes comprise about 30% of the peninsula area. The dunes occur as elongate east-west fingers of sand that are interspersed with vegetated and partially vegetated dunes (Figs. 4A, 6). Movement is effected by the strong onshore winds. The dunes begin as parabolic blowouts on vegetated older dunes. These older dunes contain abundant *in situ* calcified root casts and cemented laminae. As sand is mobilised, surface lags of the calcified casts and limestone plates (cemented laminae) form (Fig. 8D); these undergo later solution and disintegration by rainwater and the $CaCO_3$ is redistributed. The advancing eastern edge of mobile dunes progressively engulfs the established heaths, forests and woodlands (Fig. 4B) and buries the soil sheet upon which this vegetation grows (Figs. 8A, 8B, 9).

The internal structure of migrating dunes contains large scale cross-bedding and cross-lamination (Fig. 8D). The sediment of dunes is medium and fine sand (mostly quartz and calcareous components). There is compositional and textural variation at the scale of dunes and at the scale of laminae. The $CaCO_3$ content of individual samples varies from $< 1\%$ to 30% reflecting the variable composition of source material and the variable history of a dune. For instance, a dune with 5% $CaCO_3$ may overlie or be juxtaposed against a dune with 10-15% $CaCO_3$. There is similar wide variation in grain size and composition of laminae, which may be fine sand alternating with medium sand, or fine/medium sand mixtures alternating with medium sand; coarse sand and (thin shell) granule laminae also occur.

In the Leschenault study area, there is a large range of particles (differing in size, shape, composition and internal texture) that become exposed to enable mobilisation by wind (Table 4). The wind conditions which produce mobilisation are relatively consistent for a considerable period (e.g. south-west afternoon sea breeze through summer) and deposition of material is selective according to the combination of particle aerodynamics and the differential wind field across the dune. It follows that dune laminae deposited under consistent wind conditions are texturally and compositionally varied, depending on source and availability of sand grains. Variation in wind strength and direction produces grain size, as well as compositional, variation.

Vegetated dunes. Vegetated dunes are similar in external geometry, internal structure and sediment variation to mobile dunes. They develop when mobile

Table 4

Particle types composing the dune sands.

Grain size	Typical grain composition and shape
Very fine sand	Ilmenite and rutile grains, equant shape
Fine and medium sand	Quartz grains, equant shape. Solid $CaCO_3$ grains, equant shape (e.g. lithoclast, fragments of molluscs and urchins). Porous $CaCO_3$ grains, prolate shape (e.g. calcareous algae segments). Porous $CaCO_3$ grains, equant shape (e.g. foraminifers).
Coarse sand	Quartz grains, equant shape. Solid $CaCO_3$ grains, bladed shape (e.g. mollusc fragments). Porous $CaCO_3$ grains, prolate shape (e.g. calcareous algae segments).
Granule	Solid $CaCO_3$ grain, bladed shape (e.g. mollusc fragments).

dunes become progressively fixed by heath plants, (*Acacia, Anthroceris, Rhagodia*, etc.). A surficial sheet of soil develops under plant cover and, in time, dunes degrade to more gentle slopes. Surface soils become thicker (0.3-1 m), less calcareous, and mature in terms of organic content. The more soluble soil components (carbonate) are redistributed. Root systems (live and calcified) pervade the sands; calcified root structures become more abundant at depth.

The vegetation assemblage on the dune then matures. *Acacia-Anthroceris-Rhagodia* heath tends to remain on the exposed areas, hill crests and northern side of the dunes. *Agonis* (peppermint) forests tend to develop on the southern sides and in the hollows. The inter-dunal hollows preferentially accumulate humic material and develop characteristic thicker soil.

Woodland plain. This is a relatively flat surface typically covered by discrete groves comprised of tuart (*Eucalyptus gomphocephala*), peppermint (*Agonis flexuosa*), tuart/peppermint or *Acacia*. The plain is underlain by a soil (0.3-2 m thick) which overlies either a thin profile (2-3 m) of degraded dune sand or a calcrete sheet.

Alteration of sediments. There are several physical, chemical and biological processes that rapidly alter sediments in the surface and subsurface after deposition. The most obvious alteration products of the processes are soils, calcrete and sparry calcite cementation.

The soils of the peninsula, although volumetrically minor, are structurally and geomorphically important. Structurally because they are linked with and influence the groundwater regime; geomorphically because they indicate buried older heath-covered dune surfaces and woodland-covered plains (Fig. 9). The soils, humic calcaric regosols (Bridges 1970), are sands with a high humus content and are equivalent to the Ucl. 1 soils of Australian soil scientists (Northcote *et al.* 1975). They are forming today as 1-2 m

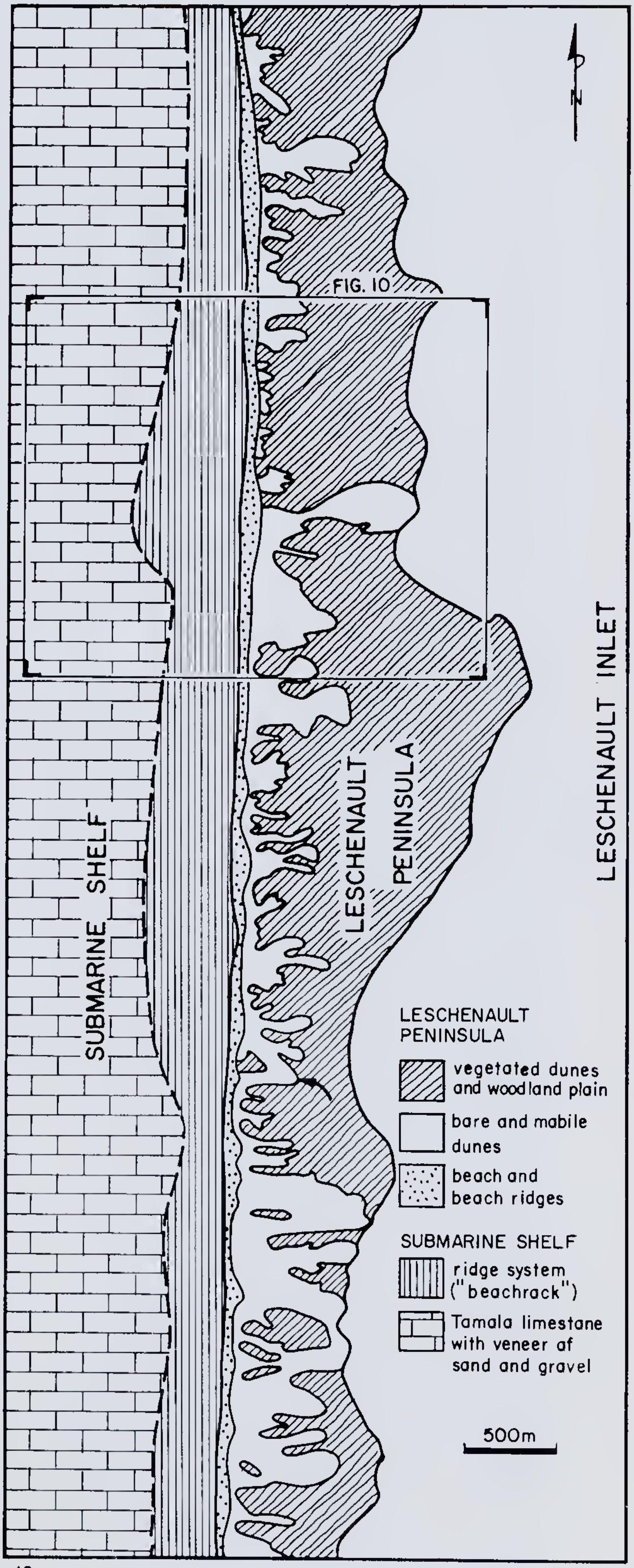


Figure 6.—Map showing geomorphic elements of the Leschenault Peninsula and the submarine shelf. Location of this area is shown in Figure 1. The arrow shows location of the dune illustrated in Figure 4B.

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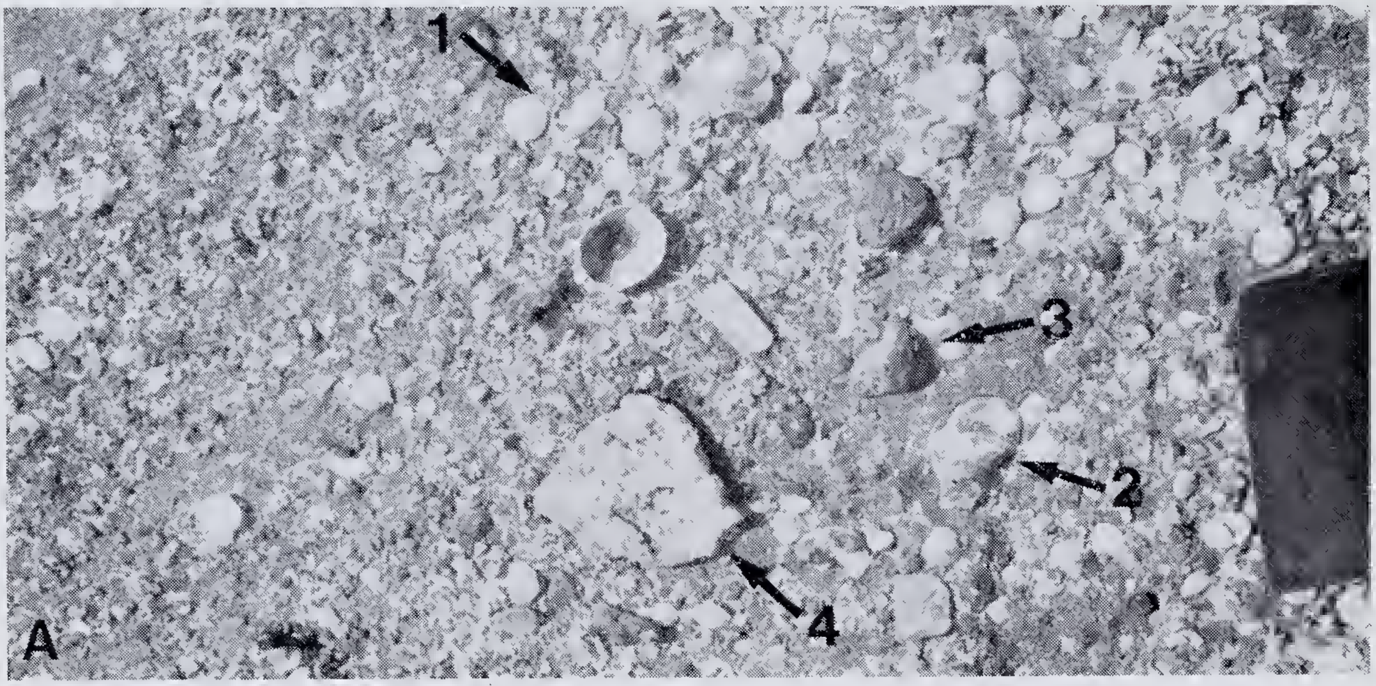


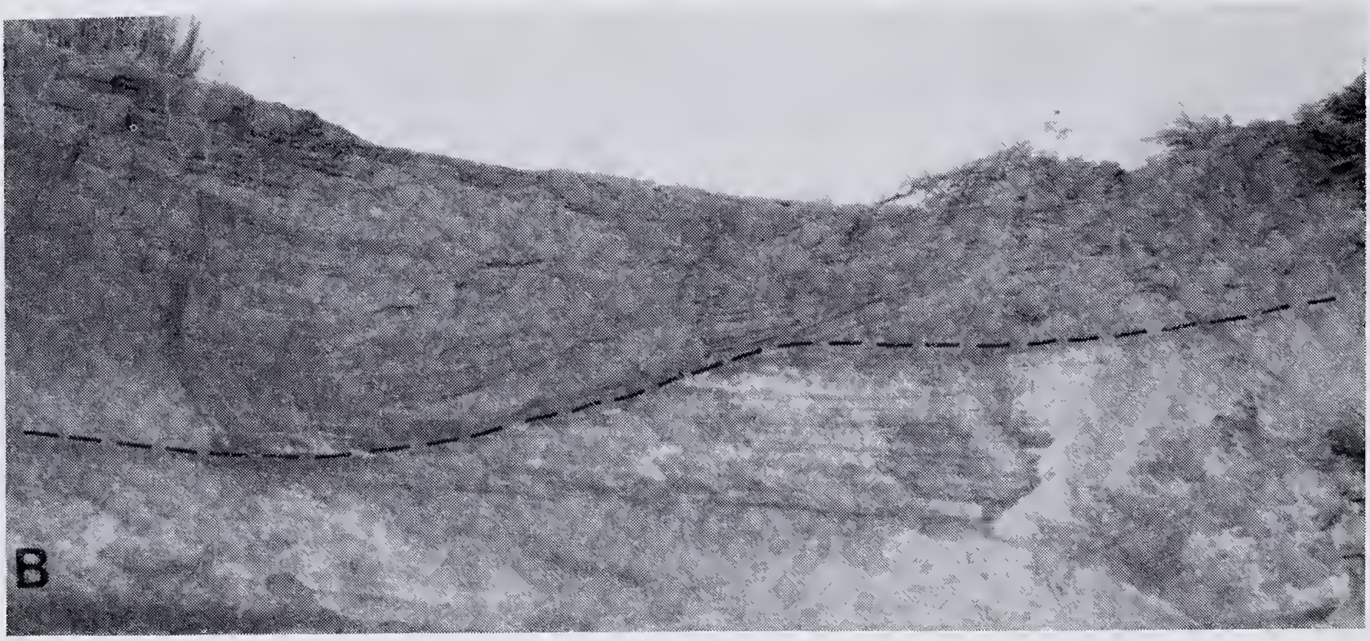
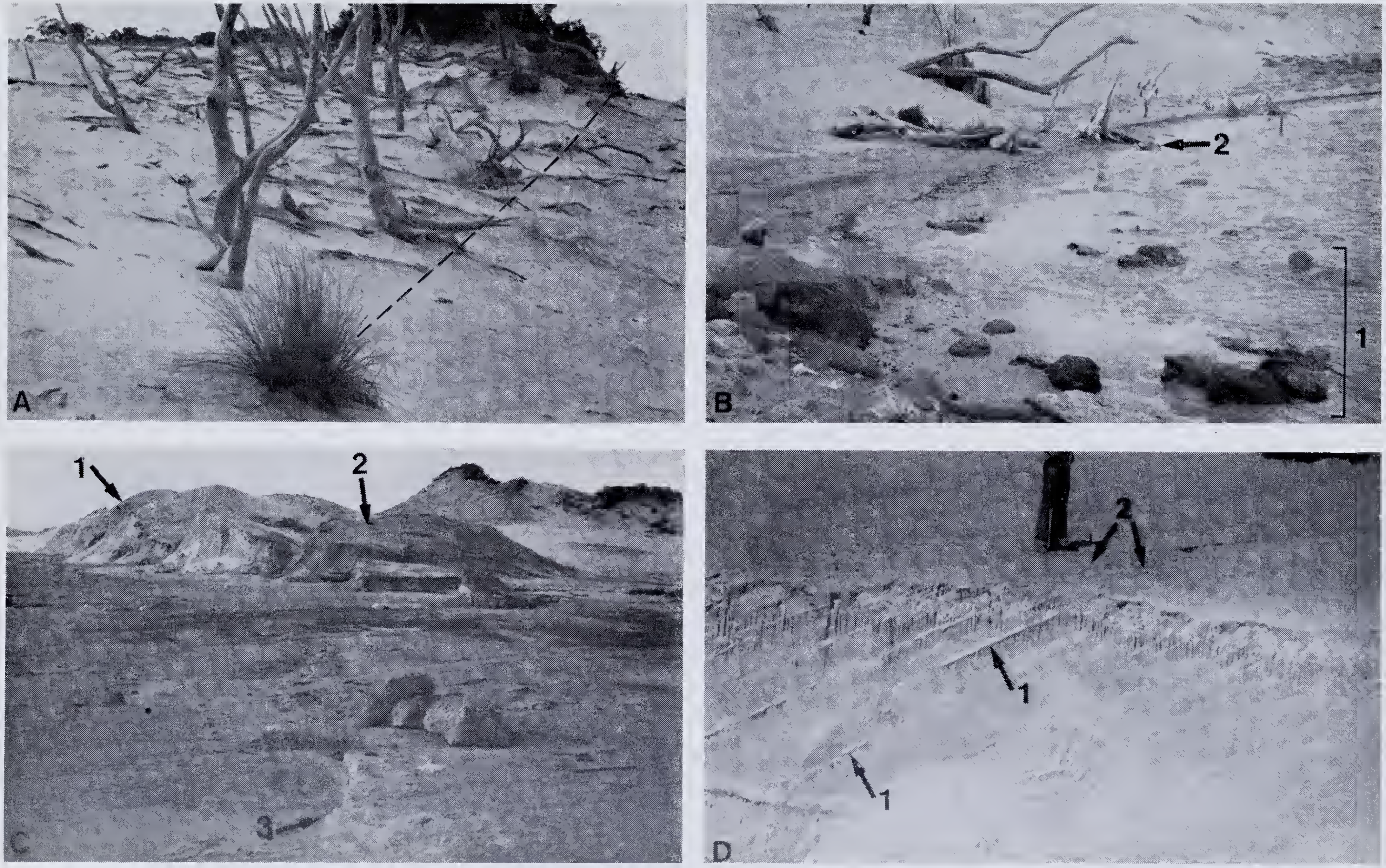


Figure 7.—A.—Surface gravel on beach face illustrating the range of gravel types. 1, recent nearshore bivalve, 2, estuarine oyster reworked from offshore mud outcrops, 3, platy limestone fragment reworked from offshore limestone reefs, 4, rounded basalt pebble. B.—Internal structure (cross-stratification) of beach ridge exposed by storm erosion following Cyclone Alby. The sharp contact between (young) orange-stained sand and (older) white sand within the beach ridge is outlined.

sheet veneers over dune sand. When buried by successive mobile dunes the soils appear in profile as undulating and bifurcating thin sheets which separate dune units. (Fig. 9).

There are 3 intergradational types of soil: (1) Dark grey humic quartz sand, which is humus rich, strongly root-structured and leached of its carbonate content. With depth it grades to a humic-rich quartz calcareous sand and then into a cream to light yellow quartz calcareous parent sand. This soil is typical of densely vegetated dunes and woodland plains. (2) Light grey to brown-grey quartz sand which is humus-poor (i.e. immature), and moderately to weakly root-structured. This soil forms on the surface of a fixed dune that supports heath vegetation.

Figure 8.—A.—Photograph showing old tuart forest on soil 3 (see Figure 10); these stumps and trunks have been exhumed by wind erosion. B.—Stratigraphy exposed in the wall of "The Cut" (Fig. 1). Trunks of tuarts and peppermints (arrow 2) are *in situ* on a soil sheet (up to 1 m thick) which is encompassed by the interval marked 1. C.—Coastal erosion following Cyclone Alby had cut back the dune line exposing stratigraphic relationships. The white sand of the old dunes is arrowed 1. Orange-stained beach ridges (arrow 2), which were developed in interdune depressions, also were truncated by the coastal erosion. The calcrete sheet (arrow 3) had been exhumed, cliffed and broken in to large blocks by the storm. D.—Dune cross-stratification exposed in a costean. Arrows 1 indicate cementation along laminae which now stand out in relief. The natural wind-deflated surface is littered with a lag of limestone plates (arrow 2) derived from these cemented laminae.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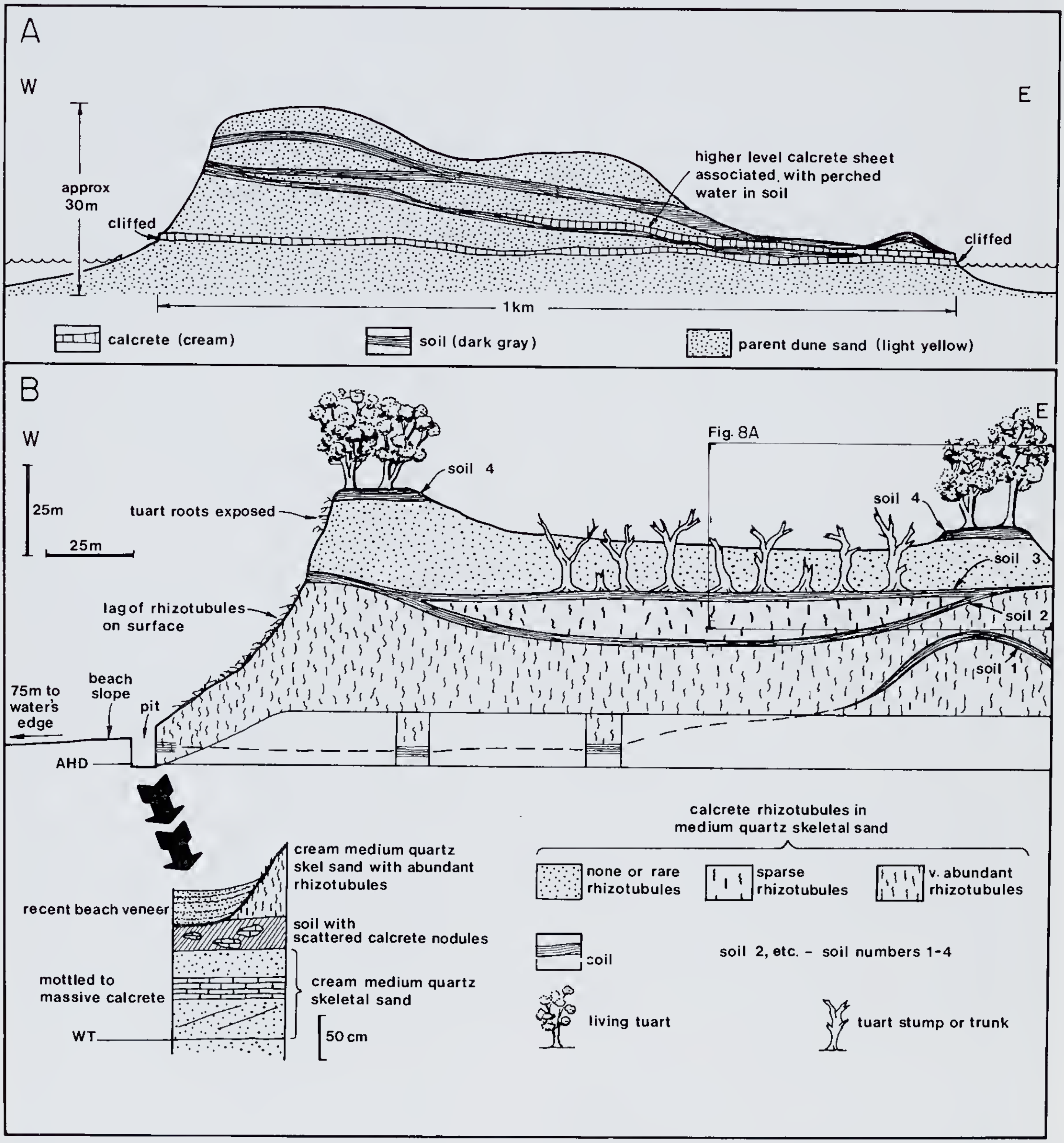


Figure 9.—A.—Diagramatic representation of stratigraphic relationships of dune sand, soils and calcrete across Leschenault Peninsula. B.—Profile along transect 3 (Fig. 1) illustrating shallow stratigraphy. Bifurcating soils separate various dune sand bodies. A fossil tuart forest is *in situ* on soil 3. The entire stratigraphic interval is cliffed to seaward. Wind erosion has sculptured the surface above the beach face; wave (storm) erosion has truncated the sequence at the level of the pit, and beach sands overlie the erosional surface.

(3) Brown-grey calcareous quartz sand with little humus content; it is moderately to weakly root-structured and occurs where inblown sand has diluted the humus contribution. This soil forms under cover of sparse vegetation on recently fixed dunes.

Calcrete is a fine-grained aggregate of $CaCO_3$ developed as a thin widespread sheet above the water table (specifically in the upper capillary zone). It forms under the dunes by evapo-transpiration. The calcrete has a number of structural forms (mottled, massive, laminar) that reflect stages in its development. The calcrete sheet is truncated by marine erosion, and occurs cliffed at the west margin of the peninsula (Figs 8, 9); on the east margin it is either cliffed or locally buried by mobile dunes (Fig. 9).

In the subsurface there also is local and patchy cementation of sand by *sparry (low magnesium) calcite* (Fig. 8D). At its maximum development about 30% of the profile may be cemented. The cementation is mostly incomplete, and crystals merely fringe and bind grains into coherent aggregates. The disposition of the cement results in selective induration of sand laminae. Most of the cementation has been observed in sand deep in the dune profile but above the present water table.

Relative age sequence in dunes. Cliff exposure and trenches indicate that cementation of sands is largely confined to older dunes low in the profile and it is on criteria of cementation, occurrence of calcified root casts (rhizotubules or rhizoconcretions) and calcrete that relative ages of sequences within the dunes are recognised. Modern dunes are uncemented and lack even calcified root casts. Older dunes contain a moderate amount of calcified root casts and are irregularly cemented in scattered patches (Fig. 9). The oldest dunes contain abundant calcified root casts and are irregularly cemented by calcrete and sparry calcite throughout much of their profile (Fig. 9). Older dunes and associated soil sheets are traceable to below present sea level indicating dune emplacement and soil formation before the Holocene sea reached its present level.

Submarine shelf

The submarine shelf is a gently sloping feature extending from low water to over 20 m depth (Fig. 2A). The sea floor directly offshore the peninsula in the study area is composed of 5 materials: (1) outcrop of Tamala Limestone, (2) beachrock, (3) estuarine mud, (4) unconsolidated sediment and (5) basalt.

Most of the sea floor in the kilometre adjacent to the study area of the peninsula (Figs. 6, 10) is formed of Tamala Limestone. It has been observed in this study to occur at depths of 18 m or more (some 8 km offshore). The general line of reef outcrops follows the general orientation of the present coastline (Fig. 6). Within 1 km of the shore, local knolls (reefs) protrude into shallow depths at random locations nearshore and along the beach. The submarine limestone topography varies from pavements to rugged reef. The pavement outcrops are veneered by sands through which limestone outcrop or reef (up to 2.0 m high) may protrude. In larger rocky reef outcrops karst and weathering features (such as caves, vugs, crevices, pinnacles, solution pipes and calcrete) are evident.

In an elongate area essentially parallel to the length of the peninsula and between low water and 6 m depth the shelf is dominated by ridges of "beachrock". The ridges, 1-4 m high and 100-300 m apart, are sub-parallel to the shore (Figs. 6, 10). Marine erosion is controlled by sedimentary structure and has resulted in a craggy slab-like to stepped surface morphology. Sand locally veneers these ridges but more commonly, forms shallow accumulations within inter-ridge depressions.

The ridges are composed of marine-indurated (cemented) sands, gravelly sands and shelly sand (informally termed "beachrock" in this study) that are similar to beach sediments onshore. The sediments are cemented by magnesian calcitc crystals; in contrast, Tamala Limestone and the dune sands of the peninsula are cemented by low magnesium sparry calcite and calcrete. The cementation, that is quite marked in the submarine environment and in the phreatic marine zone under the beach face, occurs in a zone 3-4 m thick. Whilst the relics of former ridges of beachrock remain offshore and cementation is present beneath the beach, the zone of induration is not traceable to any extent under the peninsula. The beachrock cementation appears to have taken place in the phreatic zone under the beach face where outflowing fresh water and marine phreatic water adjoin (mix) and is similar to beachrock formation described from tropical regions (Bricker 1971).

The continuing coastal erosion along the beach face removes sands overlying newly formed beachrock and exposes the cemented zone. Progressive coastal erosion thus leaves in its wake, ridges and sheets of beachrock (Fig. 10). Newly exposed beachrock is subject to wave attack and biological erosion and, in time, is broken down. All stages of beachrock exhumation and disintegration are now evident along the nearshore area adjacent to the Leschenault Peninsula.

In local areas estuarine sediment (interlayered shelly mud and sand) occurs at levels of about − 1.5 m to − 8.0 m below AHD beneath the dune sands of the peninsula, as well as under Leschenault Inlet. In general, submarine outcrop is limited but there is an extensive (pavement) exposure offshore from "The Cut" (Fig. 1); the western margin of the outcrop is terminated by a cliff 0.5 m high.

Inshore, along the peninsula shoreface and flooring areas in depressions between ridges and rocky limestone knolls, are extensive but shallow, accumulations of unconsolidated sediment; these also locally veneer the top of rocky areas. The sediment is mainly sand, gravelly sand and shelly sand, that is bare and rippled or colonised by weed. Internally, this sediment is laminated and cross-laminated. Sources of sand are local (erosion of limestone and "beachrock" ridges), onshore (beach) and offshore. Shells are from encrusting communities on nearby rock reefs, and from resident animals in the sediments. Rock gravel is derived from the nearby limestone reefs and basalt outcrops. Locally, there are small accumulations of mud clasts and estuarine oysters recently reworked from estuarine muds that crop out on the sea floor.

Further south in the vicinity of Bunbury and its harbour the shelf is a relatively smooth flat pavement of fresh basalt and eroded weathered basalt covered locally by sand, gravel or mud.

Geomorphic processes

The major processes important to the development of the Holocene geomorphology and history of the area are sedimentation and erosion.

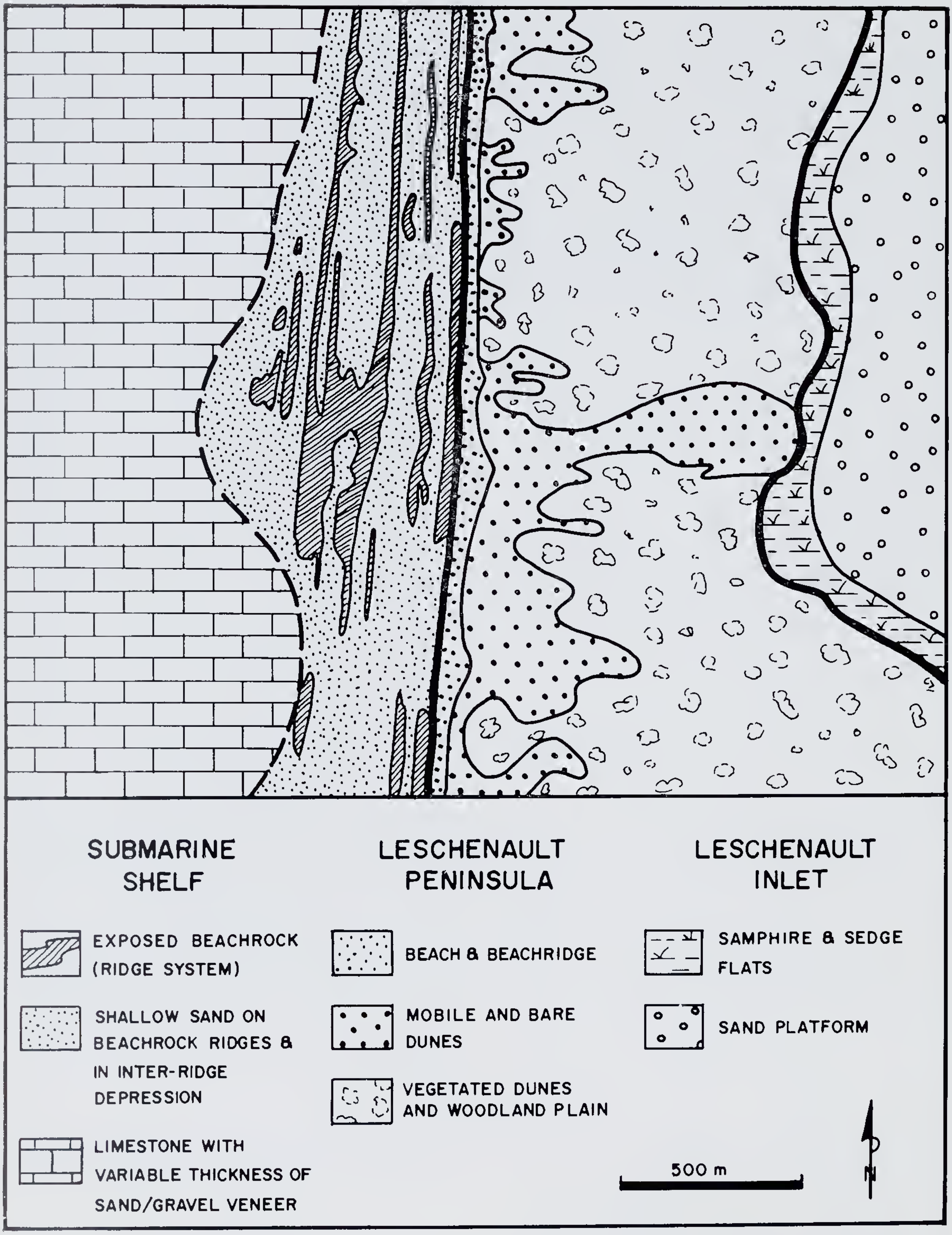
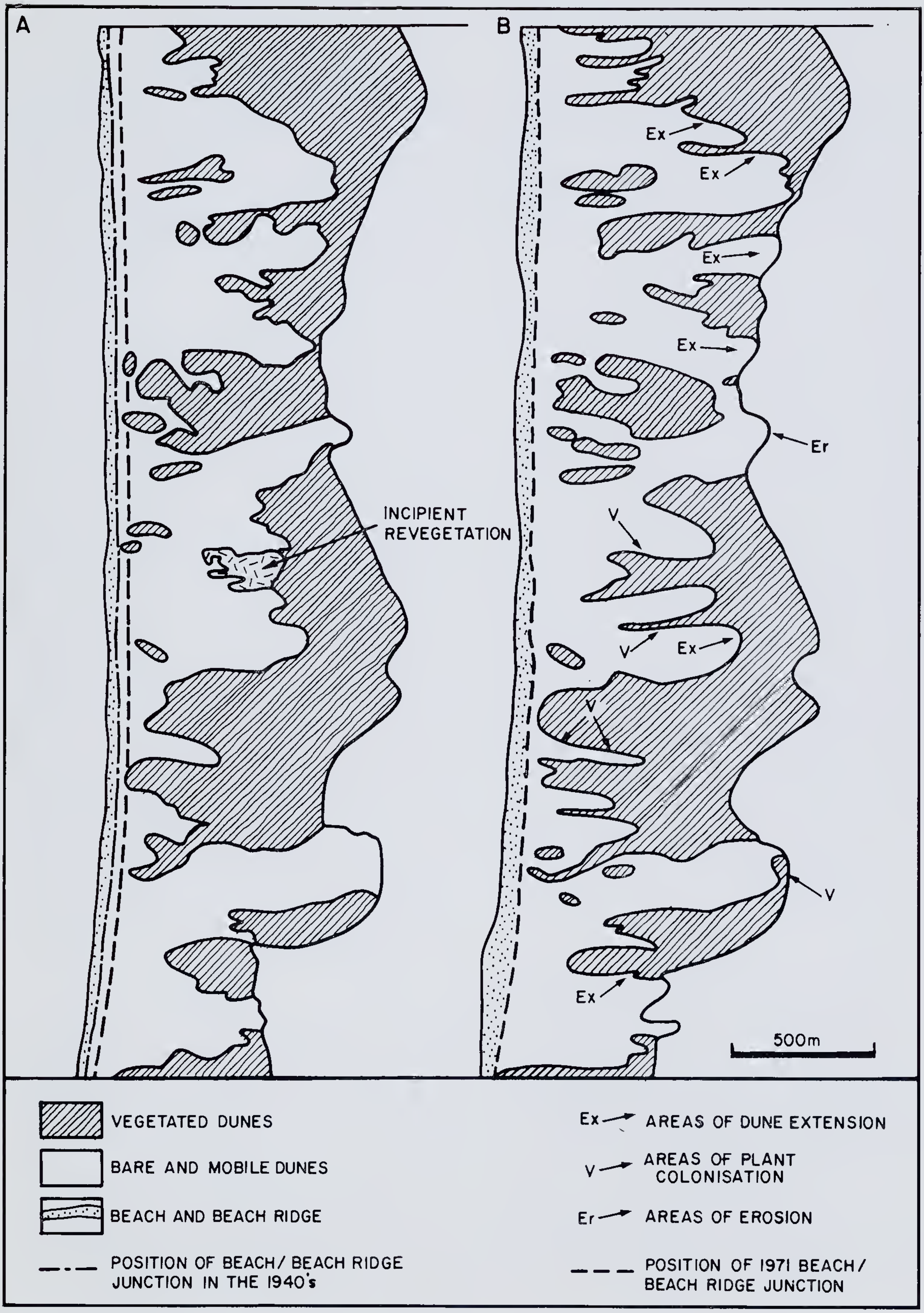


Figure 10.—Detailed map of geomorphic elements across submarine shelf, Leschenault Peninsula and Leschenault Inlet. Locality is shown as inset on Figure 6.

Figure 11.—Maps drawn from aerial photographs (A, 1941; B, 1971) illustrating extent of coastal erosion, dune encroachment and revegetation. Some of the more obvious changes are labelled.


A
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INCIPIENT REVEGETATION
Ex
Er
V
500m
VEGETATED DUNES
BARE AND MOBILE DUNES
BEACH AND BEACH RIDGE
POSITION OF BEACH/ BEACH RIDGE JUNCTION IN THE 1940's
Ex → AREAS OF DUNE EXTENSION
V → AREAS OF PLANT COLONISATION
Er → AREAS OF EROSION
POSITION OF 1971 BEACH/ BEACH RIDGE JUNCTION

Sedimentation

The main sedimentation sites are Leschenault Inlet, the peninsula dune system and the beach/beach ridge shoreface. Leschenault Inlet is filling with sand from (dune) margins, and with mud in the central portions. Sedimentation is more rapid on the peninsula where extensive mobile dunes are periodically developed. The mobile dunes extend as attenuated parabolic forms burying older dune topography. They ultimately spill into the inlet, contributing to shoals and platforms.

Examination of aerial photographs (between the 1940s and 1979) shows that 3 or 4 dunes in an area along some 3 km of peninsula significantly extended further eastward by 100-300 m over 30 years (Fig. 11). Blow-outs are initiated more frequently on the western wind-exposed shoreface. On-site study over 2 years indicates that some active dunes migrate at 3-10 m/year, a rate comparable with that derived from aerial photographs. The faster rates were encountered with dunes closer to the western shore. Dune migration is clearly staggered; dunes formerly mobile, are now fixed, and new blow-out sites are continually developing.

Sedimentation occurs on a seasonal basis on the beach shore. The beach face (foreshore and backshore) varies in width from 50 m in winter to $>$ 100 m in summer. The sediments are in definite stratigraphic sequence: subtidal, trough-bedded sands and gravelly sands, overlain by swash-zone, laminated sands, overlain by storm-level sands and shelly sands. The sediment suite forms a shore-fringing wedge or ribbon that is continually migrating to eastward as the coast erodes.

Beach-ridge sedimentation, in contrast, is localised in small hollows or embayments. There is little opportunity for beach ridges to form against a steep eroding cliff line, but in the larger interdune depressions (wind-eroded hollows) gradients are low and beach ridges develop. There is characteristic (1 m-sized) cross-stratification and a covering of vegetation (Fig. 7B).

In the context of retreating coastline, the existence of beach ridges in the hollows is temporary; coastal erosion ultimately incises them. New localities however are continually being exposed in which beach ridges can develop.

Erosion

Erosion is widespread and important on the western peninsula shore where it is a dominant factor in developing both the coastal morphology and submarine shelf. Elsewhere it is relatively minor and alternates with sedimentation. Two types of erosion predominate, wind erosion and wave erosion.

Wind erodes sand on the western face of the peninsula, continually exposing roots of living plants and leaving surface lags of cemented materials (Fig. 9). The effect of wind in this situation of limited sand supply from nearshore/offshore areas is slow, but the result is net erosion.

The foreshore along the Leschenault Peninsula changes seasonally from a full summer beach to a depleted winter beach. Periodic major storms and cyclones result in severe erosion. The vegetation line at the back of the beach is eroded (Fig. 8C) during those occasional storms that coincide with low barometric pressure and a correspondingly elevated mean sea level. During 1978 two such storms occurred. Coastal retreat of up to 30 m was recorded following the storm in March and Cyclone Alby in April. Water was elevated by 2 m and wave action cut into the toe of dunes collapsing the cliffs (Fig. 8). After these storms the beach was inspected before the fresh cliff face of sand collapsed. Although the beach is relatively consistent in alignment, the exposure showed that some new areas were exhumed (as indicated by a collapse of the protruding calcrete sheet Fig. 8C)). At other locations the storms had truncated beach-ridge debris which had been deposited and buried in the past 10 years (Fig. 7B). Thus, the two storms did not result in uniform erosion along the same coastline.

A review of the photographic record shows that whilst there are minor short term oscillations in beach line there has been overall net erosion of the beach face in the past 35 years (Fig. 11). Comparison between 1941 and 1971 aerial photographs shows that the coast suffered a net retreat of about 30 m; between 1971 and 1978 there was negligible erosion, however, in 1978 the coast retreated locally up to 30 m.

In summary, it is evident that coastal retreat is proceeding consistently and slowly by wind erosion, more moderately (1-2 m/year) by seasonal storms and winter waves, and rapidly but sporadically by periodic large storms and cyclones. The result is net erosion.

The influence of erosion on the coastal morphology is direct. Firstly, the entire western shoreface is steeply cliffed with exposures of roots and internal dune features (soils, laminae, cemented zones). Surficial sediments are stripped away and older stratigraphic units are exposed (Figs. 8, 9). For instance, calcrete and soils that crop out on the shore face are cliffed on a seasonal basis and eroded back by up to 1-2 m/year; these small cliffs are buried by the beach sediments in the following summer. Erosion of older sedimentary units contributes sand to the next sedimentation cycle. Secondly, as the coast retreats, it leaves in its wake, a newly exposed band of beachrock (Fig. 10). The net retreat is clearly reflected in the parallel bands of beachrock that form the submarine ridge system of the shelf. The extent of the beachrock indicates that at least 0.5 km of retreat has taken place leaving a vast expanse of cemented rock.

Discussion

Four major points of interest arise from this study. All of these have local implications for the Australind-Leschenault Inlet area, but some have more regional implication for the development of the Swan Coastal Plain. The first is that erosion is a dominant geomorphic process on this portion of sea-exposed coast. This conclusion has been reached by Silvester (1961) and Kempin (1953) for other coastal areas of the Swan Coastal Plain.

Extrapolation of erosional rates derived from the study area (1-2 m/year) into the past suggests at least 1 km of coast has been lost every 1 000 years. This width seems excessive, but even with more conservative estimates, erosion has been the main event in the more recent Holocene at least for this area, i.e. the Holocene sea has done nothing but erode sediments here since it reached its present level some 3 000-4 000 years ago (Semeniuk in prep.). Stratigraphic evidence (Semeniuk, in prep.) also indicates that the bulk of the peninsula did not form by progradation of coastal sediments with sea level at its present position. It appears therefore that erosion has been a long term continuing event rather than a short-term event of the more recent Holocene.

Aeolian action, which is relatively quite slow, is redistributing sand toward the east in a series of staggered advances. Marine erosion is far more rapid and severe, and it is responsible for marked shore retreat. The beach sediment at present is characteristically stained orange (Figs. 4A, 7B) and would be quite diagnostic wherever it is deposited.

The bulk of this eroded material does not find its way into the onshore dune environment (Fig. 4A) but is transported north by longshore drift. Beaches north of Myalup (some 25 km north of Bunbury) which were white less than a decade ago, are now receiving orange sand. In contrast, beaches south of the study area are still white. The northward movement of sand has been recognised previously by Kempin (1953) working on coastal areas between Cockburn Sound and Scarborough.

The next point of interest concerns the final resting place of the coastal sands mobilised northwards by shoreline processes. Obviously some is trapped in embayments forming a prograding beach/beach ridge sequence as exemplified by Rockingham Plain. Some forms tombolos in the lee of islands and reefs and is instrumental in the development of embayments such as Cockburn Sound and Warnbro Sound. The bulk of it, however, may have moved even further north and may now occur as the massive coastal dune fields north of Yanchep.

The third point of interest relates to beachrock. The concept that shallowly submerged rocky reefs and ridges develop in the wake of a retreating coast is quite novel. This implies that some similar rocky reefs in shallow waters offshore from beaches on the Swan Coastal Plain may not be Tamala Limestone but cemented residuals of eroded coastal sands.

The final point relates to the easterly migratory sand dunes. Although their movement is staggered it may be expected that ultimately the dunes will migrate across the inlet and abut the hinterland. Quindalup dunes will impinge upon Spearwood dunes. This in fact has already occurred in the vicinity of Binningup. Any further migration would result in Quindalup dunes partially overlying Spearwood dunes. More importantly, the entire Leschenault Inlet sequence could be lost by marine erosion. Thus the variability present today from offshore to the hinterland would be reduced to a more simple west to east parallel sequence of beachrock, beach, Quindalup dunes, Spearwood dunes. This latter sequence is commonly found on the Swan Coastal Plain.

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